

QCD and Collider Processes

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Abstract

I review the status of today's theoretical description of Standard Model processes relevant for Tevatron and LHC analyses, and of the tools that are used in phenomenological studies. I will also discuss a few recent ideas to further refine our abilities to perform technically challenging calculations.

1 Introduction

Today we face many fundamental questions, some of which are driven by experimental data, such as the question about the mechanism of electroweak (EW) symmetry breaking, the nature of dark matter, and the physics associated with the vacuum energy, as well as questions that are driven by theoretical curiosity and ambition, which are in essence propelled by our hope that there is an elegant structure behind what we observe in nature. Questions of the latter type include why there are three generations, what causes the hierarchy of fermion masses and mixing, and how the strong CP problem is resolved. While questions of the first type do have a definite answer, this is not necessarily the case for the questions of the second type. From this point of view, some of these questions might not even be the right ones to ask. With the start of the LHC we feel that we are at a verge of big changes, the depth of which we can not assess yet. Indeed, the LHC marks the start of a long research program and experiments at the LHC are expected to revolutionize our understanding of the fundamental forces and matter. The LHC will definitely explore the origin of mass and the associated nature of EW symmetry breaking. In the course of this, it might also shed light on the nature of dark matter and the origin of the matter-antimatter asymmetry. It may also explore the physics that underlies the evolution of the early universe. While it is clear that the LHC will not answer all the fundamental questions that we have, the questions we ask now will most likely change after the LHC era. It is therefore really a great and unique time to be a particle physicist.

Since the beginning of its run in 2010, the LHC has been remarkable successful. ATLAS and CMS collected around 45 pb^{-1} in 2010, more than 1 fb^{-1} by the time of summer conferences, and more than 5 fb^{-1} by the end of the year. At the end of the 2011 run, almost every week has set a new record in instantaneous luminosity. With the 2010 and early 2011 data, remarkably, all major Standard Model (SM) processes have already been re-established, including single-top and di-boson production, challenging measurements (because of the small/large cross-sections/backgrounds) that have been performed at the Tevatron only in recent years. By now, we have entered a new territory in the search of physics beyond the SM (BSM) with sensitivities already well exceeding those of LEP and the Tevatron.

One important question then concerns the role of QCD for LHC measurements and new-physics searches. Understanding how QCD works is essential in order to make accurate predictions for both the signal and background processes. This typically requires complex calculations to higher orders in the perturbative expansion of the coupling constant. Understanding QCD dynamics can however also help reduce backgrounds and sharpen the structure of the signal. This can for instance be achieved by designing better observables, by employing appropriate jet algorithms, by using jet-substructure, or by exploiting properties of boosted kinematics. Finally, once discovery is made, QCD will be crucial to extract the properties (masses, spins, and couplings) of the new states found. Therefore, at the LHC, no matter what physics you do, QCD will be part of your life.

It is interesting to first recall a recent measurement that was the origin of considerable excitement. In April 2011, CDF reported the observation of a peak in the m_{jj} distribution in $W + \text{dijet}$ events [1],

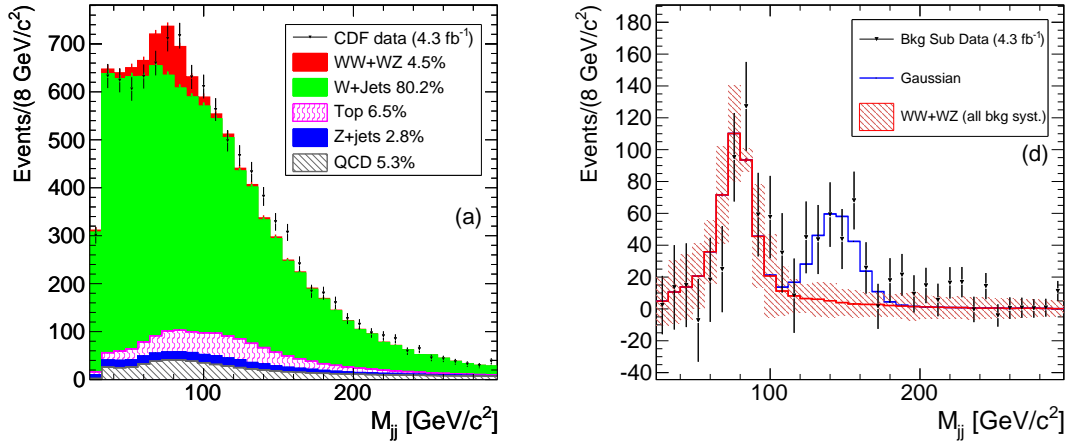


Fig. 1: The dijet invariant mass distribution for W plus dijet events as measured by CDF. The left pane shows the fits for known processes only. The right pane shows, by subtraction, the resonant contribution to m_{jj} including WW and WZ production and a hypothesized narrow Gaussian contribution. Figures taken from [1].

see Fig 1. The first measurement had a 3.2σ significance, and was based on 4.3 fb^{-1} . Subsequently, more data (7.3 fb^{-1}) has been analyzed, leading to a significance of more than 4σ [2]. Since then, a large number of tentative new-physics explanations appeared on the arXiv, along with a few SM analyses that address the question of whether this effect can be attributed to a mismodelling of one of the SM backgrounds (in particular single top) [3–5]. The excitement was curbed few months afterwards, when in June, D0 announced that it did not confirm the excess seen by CDF [6]. It is yet unclear what the reasons for the discrepancy between CDF and D0 findings are, if any. However, this example demonstrates that even in the case where one identifies a mass peak in the tail of a distribution (a scenario that was considered “an easy discovery”) a robust control of SM backgrounds remains mandatory, in particular when the shape of the backgrounds is one of the issues. Currently we have a number of other recent measurements at collider experiments that report a few sigma deviations from the SM predictions. This is for instance the case for the top forward-backward asymmetry measured by both CDF [7] and D0 [8], for the dimuon charge asymmetry measured by D0 [9], for $W + b$ measured by D0 [10], CP violation in time-integrated D^0 decays [11], and a few more.

The important question becomes then what the tools at our disposal are to make precise predictions, and whether we have the solid control of signal and background processes that is needed in order to claim discoveries. In this write-up I will discuss the status of our theoretical knowledge of most important SM processes, the tools at our disposal to describe these processes, and the impact of QCD higher orders in view of recent Tevatron/LHC results. Finally, I will discuss a few recent ideas to further improve on the way we perform technically challenging calculations.

2 Perturbative tools

The range of physics analyses that one can do at the LHC is very broad. It includes pure instrumental QCD studies, such as measurements of parton densities and inclusive jet cross-section measurements, precision EW measurements, Higgs searches, direct and indirect BSM searches, B physics, top physics, diffractive studies and forward physics, and heavy ion physics. Each of these topics includes a vast number of measurements and studies. Yet, there are three things that everybody involved in any of these analyses can not live without. These are Monte Carlos (MCs), parton distribution functions (PDFs), and jets.

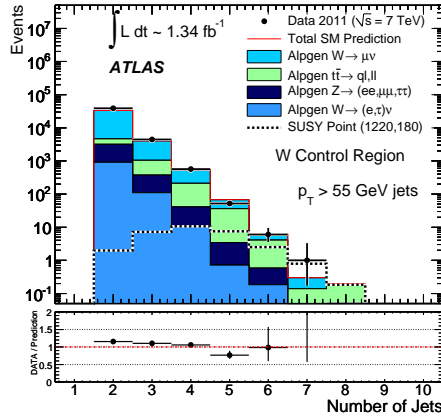


Fig. 2: The multiplicity of jets with $p_T > 55$ GeV for events in a W enriched control region at the LHC (7 TeV). Figure taken from [18].

2.1 Monte Carlos and leading order matrix elements

The first thing one can not live without at the LHC are MC generators. Apart from very few exceptions, every analysis at the LHC uses a MC program for the simulation of the signal process, for the backgrounds, for subtracting the underlying event and the non-perturbative contributions, and/or for efficiency studies and modeling of the detector response. The current level of sophistication is such that essentially not a single study relies on Pythia/Herwig alone. It is well understood that in multi-parton processes it is important to describe the multiple hard QCD radiation at least using exact matrix elements, employing for instance Alpgen [12], Madgraph [13], or Sherpa [14].

Since experimental studies rely heavily on all these leading-order (LO) tools, there is continuous progress in their development, and the Herwig/Pythia codes that we have today bear little resemblance to their original version of the '80s. In particular, in Pythia 8.1 [15] (a C++ code) there is a new fully interleaved p_t -ordered multi-parton interaction (MPI), initial- and final state evolution (the original mass-ordered evolution is not supported any longer), a richer mix of underlying event processes (γ , J/Ψ , DY), the possibility to select two hard interactions in the same event, an x -dependent proton size in the MPI framework, the full hadron-hadron machinery for diffractive systems, several new processes in and beyond the SM, and various other new features. Herwig++ [16] (the current version is 2.5.2) has new next-to-leading order (NLO) matrix elements, including weak boson pair production, a colour reconnection model, diffractive processes, additional models of BSM physics, and new LO elements for hadron-hadron, lepton-lepton collisions, and photon-initiated processes. Sherpa [14] (version 1.3.1) has improved integration routines in Comix, a simplified kinematics reconstruction algorithm of the parton shower (PS), leading to numerically more stable simulations, HepMC output for NLO events and various other improvements/bug-fixes. Madgraph [13] (version 5) has a completely new diagram generation algorithm, which makes optimal use of model-independent information, has an efficient decay-chain package, and a new library for the colour calculations. Some applications from ALOHA [17], an automatic library of helicity amplitudes for Feynman diagram computations are also implemented. Altogether, there is continuous, fast progress in various directions. So far, it is amazing how well these tools work, once the normalization is fixed using data. A very recent comparison of data with Alpgen up to six jets (a control region for BSM searches) is shown as an illustration in Fig. 2 [18]. Yet, the devil is often in the detail (i.e. in the $\sim 20 - 30\%$ effects that are opposite to expectations). For instance in general one expects matrix-element based MCs to work better than pure PSs, but this is not always the case (see e.g. [19]). Altogether, these LO programs will undergo a real stress test in the coming years.

2.2 The NLO revolution

Theorists like to advertise NLO computations by using the reduction of scale uncertainties in the predictions as an argument, which is meant to reflect the reduction in the theoretical perturbative uncertainty. However, the strongest argument in support of NLO calculations is their past success in accurately describing LEP and Tevatron data. Because of the importance of NLO corrections, an industrial effort has been devoted in the last years to these computations [20]. Recent revolutionary ideas in the way NLO computations are performed include sewing together tree-level amplitudes to compute loop amplitudes (using on-shell intermediate states, cuts, unitarity ideas, ...) [21], the OPP algorithm, an algebraic way to extract coefficients of master integrals by evaluating the amplitudes at specific values of the loop momentum [22], and D -dimensional unitarity, a practical numerical tool to evaluate full amplitudes, including the rational part, with unitarity ideas [23]. For a pedagogical review on unitarity methods see [24]. These methods led in the past 2 to 3 years to a number of $2 \rightarrow 4$ calculations at hadron colliders. These include $W + 3$ jets [25,26], $Z + 3$ jets [27], $t\bar{t}b\bar{b}$ [28], $t\bar{t} \rightarrow W^+W^-b\bar{b}$ [29], $W^+W^+ + 2$ jets [30], $W^+W^- + 2$ jets [31], $b\bar{b}b\bar{b}$ [32], $t\bar{t} + 2$ jets [33], four jet production [34], and a few other ones.

Feynman diagram methods have also been applied successfully to $2 \rightarrow 4$ calculations, this is for instance the case for quark-induced $b\bar{b}b\bar{b}$ [35], $t\bar{t}b\bar{b}$ [36], $W^+W^-b\bar{b}$ [37] production, $W\gamma\gamma$ +jet [38], and a number of vector boson fusion (VBF) processes which are available in the public code VBFNLO [39]. VBF processes have never been measured at the Tevatron. First measurements of VBF W or Z production at the LHC are therefore of particular interest. They also pave the way to measurements of VBF Higgs production. Note that only a few years ago, performing this type of calculation with Feynman diagrams was considered an impossible task.

A novel approach to NLO calculations, based on the results of [40], promotes traditional tree algorithms to generators of loop-momentum polynomials, that are called open loops [41]. The excellent performance of the method has been demonstrated, open loops have therefore a potential to address a number of multi-particle processes at hadron colliders. Another recent approach evaluates one-loop QCD amplitudes purely numerically [42]. The algorithm consists of subtraction terms, approximating the soft, collinear and ultraviolet divergences of one-loop amplitudes and a method to deform the integration contour for the loop integration into the complex space. The algorithm is formulated at the amplitude level and does not rely on Feynman graphs. The power of this method has been demonstrated recently with the leading color NLO calculation of up to seven jets in e^+e^- collisions [43].

Given that both Feynman diagram and unitarity based methods allowed us to compute $2 \rightarrow 4$ processes at NLO in QCD, it might be unclear where the revolution advocated in the heading of the subsection lies in. The revolution, I believe, is not yet in the applications that we see today, rather in the prospect for low-cost fully computer-automated NLO calculations even beyond $2 \rightarrow 4$ in the near future. Indeed, two $2 \rightarrow 5$ processes have already been computed at NLO, namely $W + 4$ jets [44] and $Z + 4$ jets [45].¹ Fig. 3 illustrates in the case of $W^- + 4$ jets the typical effect of including NLO corrections: one obtains a considerable reduction of the scale uncertainty, and, for some distributions, a change in shape. As far as the full automation is concerned, let me highlight three interesting approaches. The first one [46] is a method based on Feynman diagrams, it uses the OPP procedure for the virtual calculation, and the FKS subtraction of divergences, together with clever and efficient procedures to deal with instabilities. More improvements and refinements are to be expected soon. At present there is no public code, instead the idea is to provide N -tuples. The second approach, HELAC-1LOOP [47], is a program that evaluates numerically QCD virtual corrections to scattering amplitudes using the OPP method. The public program is part of the HELAC-NLO framework that allows for a complete evaluation of QCD NLO corrections. GoSam [48] is a third approach which aims at the full automated calculation of NLO corrections for multi-particle processes. The one-loop amplitudes are generated using Feynman diagrams and are reduced using D -dimensional unitarity, a refined Passarino-Veltman style tensor reduction, or a combination of

¹In both cases the leading colour approximation has been used. This approximation is expected to give rise to very small (percent) corrections only.

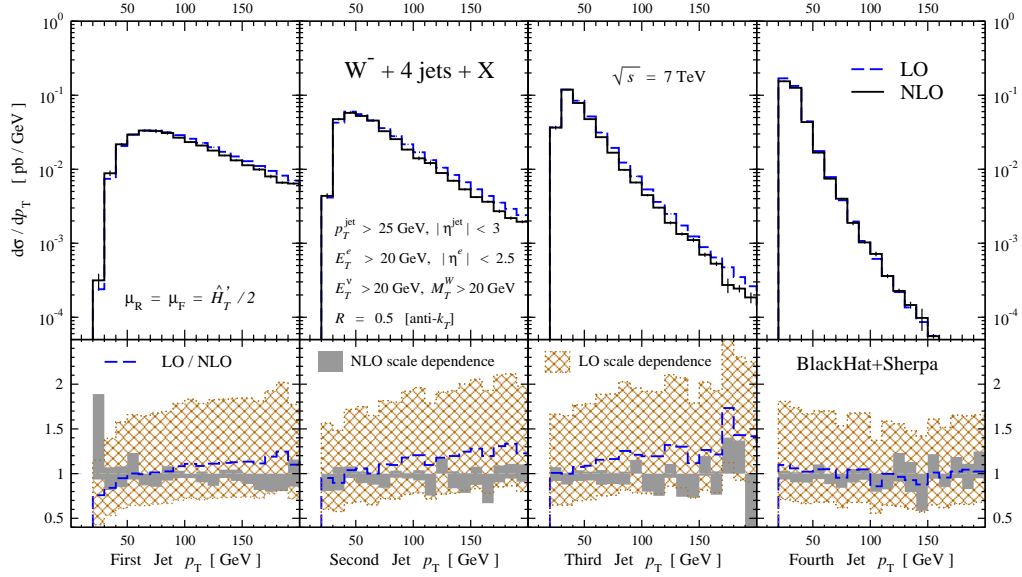


Fig. 3: The transverse momentum distribution of the leading four jets in $W^- + 4\text{-jet}$ production at the LHC (7 TeV) at LO and NLO. The lower panels show the LO and NLO scale-dependence bands ($\hat{H}_T'/4 \leq \mu_R = \mu_F \leq \hat{H}_T'$) normalized to the central NLO prediction ($\mu_R = \mu_F = \hat{H}_T'/2$). Figure taken from [44].

both. GoSam can be used to calculate one-loop corrections to both QCD and electroweak theory, and model files for BSM theories can be also linked. An interface to programs calculating real radiation is included too. The flexibility of GoSam has been demonstrated explicitly by considering various examples.

2.3 Merging NLO and Parton Showers

While NLO predictions provide relatively accurate results for inclusive cross-sections, they do not furnish an exclusive description of the final state that can be compared with actual particles in the detectors, as MC programs do. It is therefore useful to combine the best features of both approaches. Two public frameworks exist for this purpose, namely MC@NLO [49] and POWHEG [50]. These tools are almost 10 years old now, and since their conception a long list of processes has been implemented in both frameworks. In particular, recently the POWHEG BOX was released [51], which is a general framework for implementing NLO calculations in shower MC programs according to the POWHEG method. The user only needs to provide a simple set of routines (Born, colour-correlated Born, virtual, real, and phase space) that are part of any NLO calculation.

Similarly, aMC@NLO is a novel approach to a complete event generation at NLO. aMC@NLO has been used recently for the calculation of $W/Zb\bar{b}$ [52] and W +dijet production [53]. Fig. 4 (left) shows an application to Higgs searches of the $W/Zb\bar{b}$ calculation: the invariant mass of the pair of the two leading b -jets, for the processes Wbb , Zbb , WH , and ZH . The figure illustrates a case where signals and irreducible backgrounds are computed with the same accuracy. The process $Wb\bar{b}$ has been implemented shortly before also in the POWHEG BOX [54].

Fig. 4 (right) illustrates predictions from aMC@NLO for the invariant mass for the dijet system in Wjj (the observable mentioned in the introduction where CDF observed a large deviation from the SM). CDF and D0 estimate the Wjj using a leading order Monte Carlo (LO+PS) re-weighted to the NLO cross-section or to data. With aMC@NLO instead it is possible to compute directly the Wjj cross-section at the NLO+PS level. It was therefore particularly interesting to check whether there is any shape difference between LO+PS and NLO+PS in the M_{jj} distribution. The study of ref. [53] shows that there is no sizable shape difference. Another interesting application of aMC@NLO is the calculation of scalar and pseudo-scalar Higgs production in association with a $t\bar{t}$ pair [55].

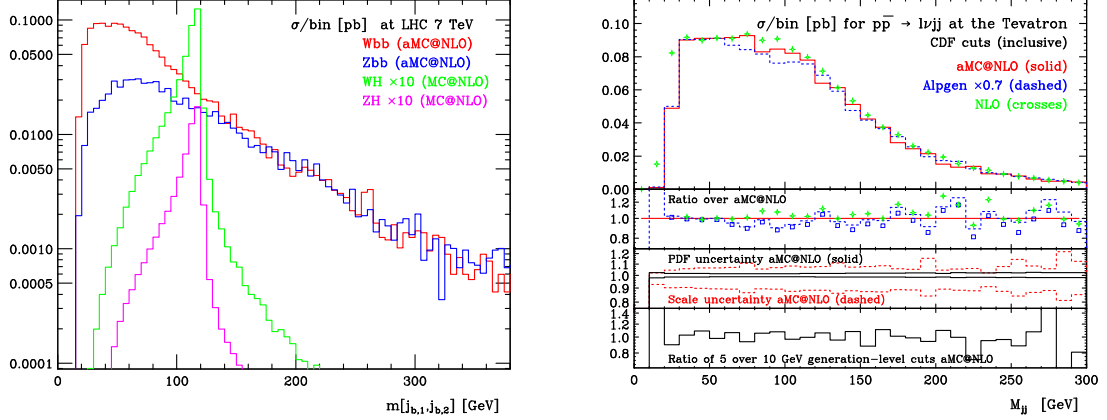


Fig. 4: Left: Invariant mass of the pair of the two leading b -jets for $Wb\bar{b}$, $Zb\bar{b}$, $WH(\rightarrow \ell\nu b\bar{b})$, $ZH(\rightarrow \ell^+\ell^- b\bar{b})$ at the LHC (7 TeV), the latter two are rescaled by a factor of ten. Figure taken from [52]. Right: Invariant mass of the pair of the two hardest jets in W + jet events with CDF/D0 inclusive cuts. Figure taken from ref. [53].

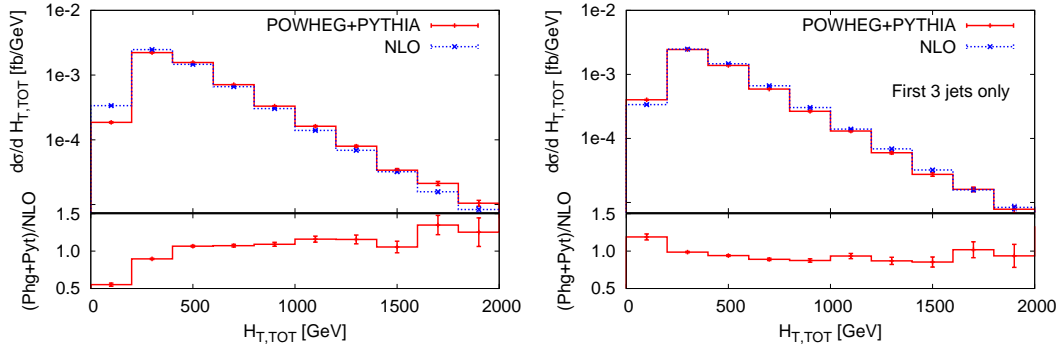


Fig. 5: Comparison of NLO and POWHEG+PYTHIA results for the $H_{T,TOT}$ distribution in the process $W^+W^+ + 2$ jets at the LHC (7 TeV), when all jets are included in the definition of $H_{T,TOT}$ (left pane), and when only the three hardest jets are included (right pane). Figure taken from ref. [56].

A lot of effort has been devoted recently also to the implementation of higher multiplicity processes in the POWHEG BOX and in aMC@NLO. The first $2 \rightarrow 4$ process that has been implemented in the POWHEG BOX is $pp \rightarrow W^+W^+ + 2$ jets including both the QCD induced part [56] as well as the VBF contributions [57]. This is a relatively simple $2 \rightarrow 4$ process since the cross-section is finite without any cut on the jets. As expected, for inclusive observables there are only minor differences between pure NLO and POWHEG+PS, but for exclusive observables, depending on the details of the observable definition, there can be important differences. This is shown in Fig. 5 for two different definitions of $H_{T,TOT} = \sum_j p_{t,j}$, the transverse energy of the event. From the figure it is clear that if only the three hardest jets are included in the definition of H_T , the corrections from the PS are very moderate (right pane), but if all soft jets present in the event are included, then additional radiation from the PS can alter the distribution substantially (left pane). The POWHEG method has been used recently also for the description of other important processes, e.g. for the calculation of Z boson in association with a top anti-top pair at NLO accuracy including PS effects [58].

2.4 MENLOPS and LoopSim

In NLO+PS approaches only contributions with one additional jet, relative to the Born contribution, are computed accurately, while all other emissions are described only in the shower approximation. There

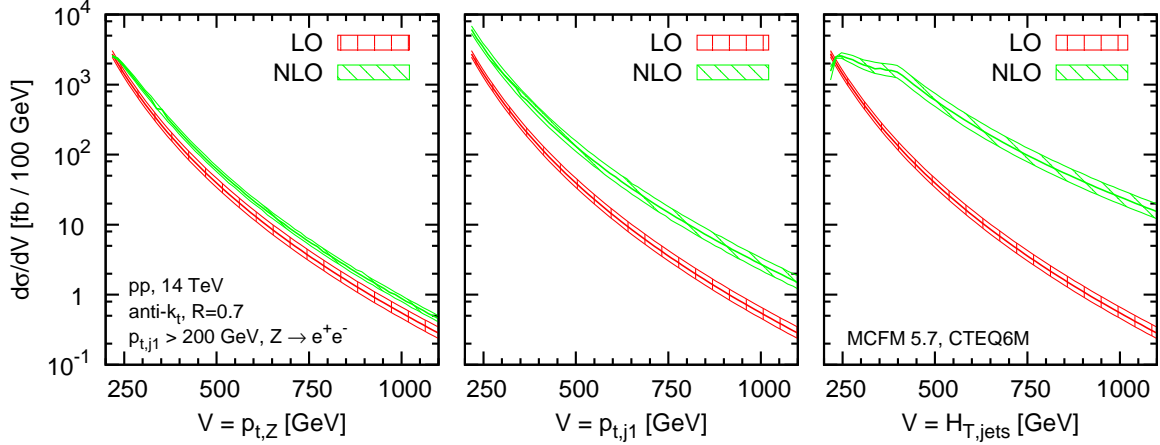


Fig. 6: The LO and NLO distributions for three observables in Z +jet production that are identical at LO: the Z transverse momentum (left), the p_t of the hardest jet (middle), and the scalar sum of the transverse momenta of all the jets, $H_{T,jets}$ (right). The bands correspond to the uncertainty from a simultaneous variation of $\mu = \mu_R = \mu_F$ by a factor of two around the default $\mu = \sqrt{p_{t,j1}^2 + m_Z^2}$. Figure taken from [61].

are however situations in which one has important contributions from higher multiplicity final states (e.g. because of new channels that open up that are enhanced by kinematical factors, gluon PDFs etc.). MENLOPS [59,60] is a method to further improve on NLO+PS predictions with matrix elements involving more partons in the final state. For example, for W production it includes, as in MC@NLO or POWHEG, W production at NLO, the PS, but also $W + 1, 2, 3, \dots$ jets using exact matrix elements. Roughly speaking, it uses a jet-algorithm to define two different regimes, and then corrects the 1-jet fraction using exact matrix elements and the 2-jet fraction using the NLO K -factor. This achieves NLO quality accuracy for inclusive quantities but an improved sensitivity to hard radiation and multi-parton kinematic features.

A further recent theoretical development is LoopSim. If one considers the process $W + 1$ jet, the three observables $p_{t,Z}$, $p_{t,j}$, and $H_{T,jets} = \sum_j p_{t,j}$ are identical at LO. However, as illustrated in Fig. 6, at NLO $p_{t,Z}$ has a moderate K -factor ($\lesssim 2$), $p_{t,j}$ has a large K -factor (~ 5) and $H_{T,jets}$ has a giant K -factor (~ 50). The very large K -factors in the last two observables are due to the fact that the NLO result is dominated by configurations where there are two hard jets and a soft W (these are enhanced by EW logarithms), additionally there is an important enhancement coming from incoming qq channels. LoopSim [61] is a procedure that uses a sequential algorithm, close to the Cambridge/Aachen one, to determine the branching history, “loops” over soft particles (i.e. they are removed from the event and the residual event is adjusted), and it uses a unitary operator to cancel divergences. In essence, this is a way to extend a calculation that is exact at a given order in perturbation theory, in an approximate way to higher orders. The procedure is expected to be more accurate the larger the corresponding K -factor is. One might expect other extensions of the MLM/CKKW matching procedure along the same lines as MENLOPS and LoopSim in the near future.

3 Top-quark production

The top is the most interesting SM quark. Its large mass implies a large Yukawa coupling, which causes the top to be a prominent decay product in many BSM models. LHC data have already been successfully compared to approximate next-to-next-to-leading order (NNLO) predictions [62,63], however various approximate NNLO predictions, based on a threshold resummation, do not fully agree within quoted uncertainties [64–68]. Significant improvements in the $t\bar{t}$ cross-sections can be expected only upon inclusion of the complete NNLO corrections. A better perturbative control of the top-quark pair production cross-section is also important to further constrain gluon PDFs, to have an accurate extraction of the top

mass from the cross-section, and to improve our perturbative control over the $t\bar{t}$ forward-backward asymmetry. In fact, an almost 3σ deviation from the SM is observed by CDF, which becomes a 4.2σ effect in the high-mass region, $M_{t\bar{t}} > 450$ GeV [7]. The large inclusive asymmetry has been seen both by CDF and D0 [8], while the rise in the spectrum of the asymmetry is not confirmed by D0. One has however to bear in mind that $t\bar{t}$ production is a difficult measurement given the presence of neutrinos in the final state, the combinatorics in the reconstruction of the tops, and the limited statistics at the Tevatron. Nevertheless, various suggestions have been made recently to explain the asymmetry in terms of BSM physics, but all proposals face the problem that they have to preserve the good agreement with the symmetric $t\bar{t}$ observables, respect dijet bounds and/or must evade the stringent limits on like-sign top production. Fervid activity is therefore currently devoted towards a complete NNLO calculation of $t\bar{t}$ production (see [69] and references therein). Recently, the program Top++ was released that evaluates numerically the total inclusive cross-section for producing top quark pairs at hadron colliders. It calculates the cross-section at fixed order through approximate NNLO and it includes a soft-gluon resummation in Mellin space at next-to-next-to-leading logarithmic accuracy [70]. The program Hathor [71] also calculates the total cross-section for top-quark pair production in hadronic collisions. It includes approximate next-to-next-to-leading order perturbative QCD corrections. It also offers the possibility to obtain the cross-section as a function of the running top-quark mass. A direct comparison between the two programs is however not possible as they use a different subleading terms in the threshold expansion.

Besides the inclusive cross-section, top pair production in association with light jets, heavy partons, photons or heavy vector bosons is also interesting. We know now at NLO $t\bar{t} + 2$ jets [33], $t\bar{t}b\bar{b}$ [28, 36], $t\bar{t}Z$ [72], $t\bar{t} + \gamma$ [73], and for $t\bar{t} + 1$ jet including hard jet radiation by the top quark decay products [74]. A matching to parton shower has been recently achieved also to $t\bar{t} + 1$ jet production [75, 76].

The NLO calculation of single top in the s and t channel [77, 78] and in the Wt channel [79, 80] have also been matched to parton showers. For a discussion of recent theoretical progress in single-top physics at hadron colliders, and of aspects of single-top production in beyond Standard Model scenarios I refer the reader to ref. [81].

4 A few theoretical issues in Higgs production

Possibly the most awaited result during the first year of running of the LHC concerned Higgs searches. Currently, both ATLAS and CMS reached the expected sensitivity, around or better than the SM cross-section. ATLAS restricted the most likely mass range at 95% confidence level (CL) to the region 115.5 – 131 GeV. They observe an excess around 126 GeV, with a local significance of 3.6σ , with contributions from the main channels $H \rightarrow \tau\tau$, $H \rightarrow ZZ \rightarrow 4l$, $H \rightarrow WW \rightarrow 2l2\nu$. The global significance taking into account the look-elsewhere-effect is 2.3σ . CMS excludes the region 127 – 600 GeV at 95% CL (while their expected exclusion is 117 – 543 GeV). They could not exclude the region below 127 GeV since data has a modest excess of events between 115 and 127 GeV that appears, quite consistently, in five independent channels. The excess is compatible with a SM Higgs hypothesis in the vicinity of 124 GeV or slightly below, but the statistical significance, 2.6σ local and 1.9σ global after correcting for the look-elsewhere-effect in the low mass region, is not large enough to say anything conclusive. For both experiments, what is observed now is consistent either with a background fluctuation or with a SM Higgs boson. More refined analyses and additional data in 2012 will definitely give an answer.

At the LHC, the Higgs is mainly produced via an intermediate top loop in gluon-gluon fusion. The urge to understand the EW symmetry breaking led in the past years to the computation of the most advanced theoretical predictions for this process. For instance we now know the main $gg \rightarrow H$ production mechanism including NLO corrections with exact top and bottom quarks in the loop [82], NNLO corrections in the large m_t limit [83–85], EW corrections [86], mixed QCD-EW corrections [87], and resummation of large logarithms possibly with N^3 LO soft effects [88–93]. Threshold corrections to the boson rapidity distribution are also known [94], these higher order corrections stabilise the theoretical

predictions under scale variations. Furthermore, the most advanced codes [95, 96] allow for fully exclusive decays of the Higgs to $\gamma\gamma$, $W^+W^- \rightarrow e^+\nu e^-\bar{\nu}$, and $ZZ \rightarrow 4l$. A similar accuracy has been reached recently also in associated VH production where, because this process is an important one if the Higgs is light, the decay of the Higgs into $b\bar{b}$ has been considered [97]. NLO EW corrections to WH/ZH production including the vector-boson decays are also known [98]. As expected, the EW corrections, which are at the level of (5-10)% for total cross sections, increase with increasing transverse momentum cuts. For instance, for $p_{T,H} > 200$ GeV, which is an interesting range at the LHC, the EW corrections to WH production are of the order of -15% for $M_H = 120$ GeV.

The fully differential decay of a light Higgs boson to bottom quarks at NNLO in perturbative QCD has been computed recently in [99]. From a technical point of view, it is interesting to note that this work constitutes the first physical application of a novel method of non-linear mappings for the treatment of singularities in the radiative processes which contribute to the decay width. The program *iHixs* [102] has also been recently released, it computes the inclusive Higgs boson cross-section, including QCD corrections through NNLO, EW corrections, mixed QCD-electroweak corrections [87], quark-mass effects through NLO in QCD, and finite width effects for the Higgs boson and the heavy quarks. Furthermore, it allows the evaluation of the cross-section in modified Higgs boson sectors with anomalous Yukawa and EW interactions as appearing in some extensions of the SM [101, 102].

Given the high accuracy with which gluon-gluon-fusion has been computed, it is interesting to ask what is the actual theoretical uncertainty on this process. Unfortunately, there is today no full consensus on this question. Some more conservative estimates quote errors of the order of 40% [103] (at the Tevatron) and similar uncertainties at the LHC, while other studies suggest that the perturbative uncertainty is considerably smaller. Assigning a correct theoretical error is very important when claiming an exclusion or an excess, and, at a later stage, when making measurements of the Higgs-boson couplings, which is the only way to identify the precise nature of the Higgs boson and EW symmetry breaking. Yet, even for the main Higgs-production channel there are still some controversies and subtleties. Most controversies have to do with how different sources of errors should be combined, others concern the question of how to assign/interpret the perturbative uncertainties. I will illustrate here just two of these issues.

The soft logarithms appearing in cross-sections can be resummed using an effective theory approach. Performing such a calculation requires an introduction of a matching scale, where the full and effective theory amplitudes must agree. It is well-known that choosing a time-like (i.e. complex) matching scale effectively resums π^2 enhanced terms. In [104] it is suggested that this procedure improves the convergence of the perturbative expansion significantly, and reduces the uncertainty of the perturbative (NNLO) prediction. This approach is criticized in [105] with the arguments that π^2 are just numbers, so that there is no formal limit in which they dominate, and that only one class of π^2 terms is resummed (those that arise from the gluon form factor), but not all of them. In this context, one has to mention that perturbative QCD is often about pushing approximations beyond their formal limit of validity, and that a given approach should be judged by seeing how well it fares in practice.

The second issue I would like to mention here has to do with a jet-veto in Higgs searches. As can be seen from Fig. 7, in Higgs searches one needs to impose a jet-veto to suppress the large top background. Higgs production is then studied in 0-, 1-, 2-jet bins separately in order to maximize the sensitivity. Currently, ATLAS uses $p_{t,\text{veto}} = 25$ GeV, while CMS employs $p_{t,\text{veto}} = 30$ GeV in their Higgs searches.

In [107] the inclusive, NNLO Higgs production cross-section at the Tevatron is split into 0-, 1-jet exclusive, and 2-jet inclusive components

$$\frac{d\sigma_{\text{tot}}}{\sigma_{\text{tot}}} = 66.5\%_{-9\%}^{+5\%}(0\text{-jet}) + 28.6\%_{-22\%}^{+24\%}(1\text{-jet}) + 4.9\%_{-41\%}^{+78\%}(\geq 2\text{-jets}) = [-14.3\% + 14.0\%]. \quad (1)$$

The errors denote the scale uncertainty that is obtained by varying the renormalization and the factorization scale together around a central value $m_H = 160$ GeV by a factor of two. In an NNLO calculation of

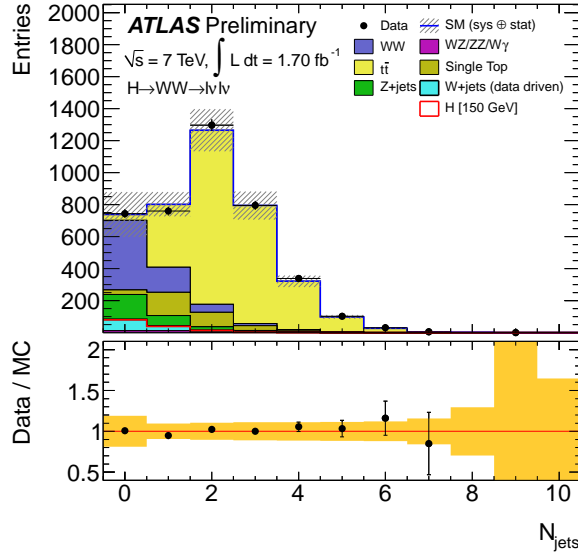


Fig. 7: Multiplicity of jets with $p_T > 25$ GeV after basic Higgs search cuts. The lower part shows the ratio between the data and the background expectation from MC, with the yellow band indicating the total systematic uncertainty in the normalization (but not the shape) of the various components. The signal is shown for $m_H = 150$ GeV. Figure taken from [106].

inclusive Higgs production, only the 0-jet bin is known at NNLO, while the 1-jet bin is known at NLO and the 2-jet bin is computed at LO only. Therefore it is not surprising that the relative errors increase with the number of jets. In [107] one can also find a detailed discussion of why it is *not* appropriate to use the standard scale variation as an estimate of the perturbative uncertainty for the 0-jet bin cross-section (Fig. 1 of [108] also shows that for a particular choice of $p_{T,\text{veto}}$ one obtains a vanishing scale uncertainty band in the 0-jet bin). The numbers in eq. (1) were updated by Campbell *et al.* in [109] who evaluated the 2-jet bin contribution at NLO. The effect of this addition was a slight change in all relative numbers, and, mainly, a decrease in the perturbative uncertainty of the 2-jet bin,

$$\frac{d\sigma_{\text{tot}}}{\sigma_{\text{tot}}} = 60\%_{-9\%}^{+5\%}(0\text{-jet}) + 29\%_{-23\%}^{+24\%}(1\text{-jet}) + 11\%_{-31\%}^{+35\%}(\geq 2\text{jets}) = [-15.5\% + 13.8\%]. \quad (2)$$

From eq. (2), it is evident that the scale uncertainty is smaller for the *exclusive* measurement with 0-jets, than the one of the fully *inclusive* measurement. To explain this feature, Stewart and Tackmann recall that there are two mechanisms at work in the 0-jet cross-section [110]: there is a large K -factor from perturbative higher orders, as well as large negative logarithms $-\alpha_s C_A / \pi \ln^2 M_H / p_{T,\text{veto}}$ that become more important the smaller $p_{T,\text{veto}}$ is. They therefore suggest that the error on the 0-jet bin should be computed taking into account a full correlation between jet-bins, i.e. the error from the 0-jet cross-section is computed from the relation $\sigma_0 = \sigma_{\text{incl}} - \sigma_{\geq 1\text{-jet}}$. One obtains then simply $\Delta^2 \sigma_0 = \Delta^2 \sigma_{\text{incl}} + \Delta^2 \sigma_{\geq 1\text{-jet}}$. The effect of this is illustrated in Fig. 8. While this procedure is certainly more conservative than a conventional scale variation, it is clear that to reduce the uncertainty on the jet-veto cross-section, a resummation of large logarithms involving the ratio $p_{T,\text{veto}}/M_H$ is required. Currently, only resummation for quantities related to the jet-veto exist, e.g. for $p_{T,\text{Higgs}}$ [111] or for the beam-thrust [112]. Both observables are however not the ones used in current Higgs searches. Furthermore the beam thrust has the drawback that it receives very large non-perturbative corrections, as can be easily seen by running a PS program once at parton and once at hadron level.

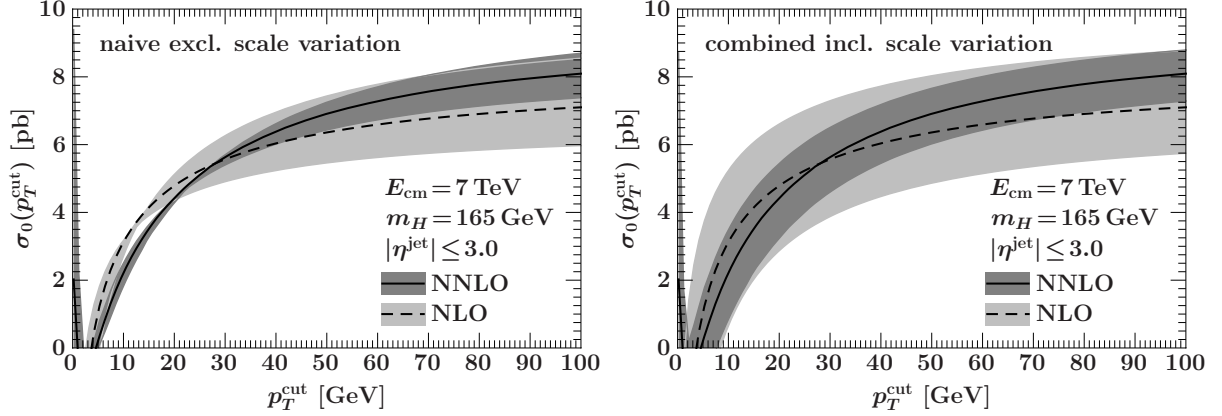


Fig. 8: Fixed-order perturbative uncertainties for $gg \rightarrow H + 0$ jets at NLO and NNLO for the LHC (7 TeV). On the left, the uncertainties are obtained from the naive scale variation in $\sigma_0(p_T^{\text{cut}})$ between $\mu = m_H/4$ and $\mu = m_H$. On the right, the uncertainties are obtained by independently evaluating the scale uncertainties in σ_{tot} and $\sigma_{\geq 1}(p_T^{\text{cut}})$ and combining them in quadrature. Figure taken from [110].

5 Gauge boson production processes

The physics programme involving gauge bosons is particularly rich. The road towards precision measurements and searches starts from the measurement of inclusive W and Z cross-sections, which, from a theoretical point of view, are the most precisely known processes at hadron colliders. Beyond measurements of purely inclusive W/Z production cross-sections, it is possible to study the production of W or Z bosons in association with one or more jets, and ratio of cross-sections. Interesting ratios are for instance $\sigma(V + (n+1) \text{ jets})/\sigma(V + n \text{ jets})$, with $V = W, Z$, that start at $\mathcal{O}(\alpha_s)$ in the perturbative expansion in the coupling constant, or ratios of $\sigma(W^\pm + n \text{ jets})/\sigma(Z + n \text{ jets})$, that are of order $\mathcal{O}(\alpha_s^0)$. In both cases, one expects many experimental and theoretical uncertainties (e.g. those related to the choice of renormalization or factorization scale, or uncertainties in the parton distribution functions) to largely cancel in the ratio. A further extension of simple ratios are asymmetry distributions, for instance the W or lepton charge asymmetry. These distributions provide strong constraints on parton distribution functions and are useful probes of new physics. Other interesting observables measure gauge bosons produced in association with heavy quarks (charm or bottom quarks). These processes are particularly interesting because of the discrepancies between theoretical predictions and Tevatron data [10], however the perturbative calculation of these processes and of the related theoretical uncertainty is challenging. Finally, di-boson cross-sections are sensitive to any type of new physics that would modify the trilinear gauge couplings, and would give rise to so-called anomalous gauge couplings. These measurements are complementary to the ongoing direct searches for beyond the SM physics, and are able to probe new-physics scales that are not directly accessible.

Fig. 9 gives the cross-section for main processes involving gauge bosons at the LHC. The figure illustrates that with 1fb^{-1} ATLAS and CMS could collect $\mathcal{O}(10^6)$ and $\mathcal{O}(10^5)$ W and Z events per experiment and per lepton channel. One also sees that, including all lepton channels, 1fb^{-1} of data contain about 100 WW and 10 ZZ events. This means that even with the data available after a first year of running, a number of interesting analyses could be performed.

5.1 Drell-Yan

The most important gauge boson production process is Drell-Yan. This is the best known process at the LHC: it has been computed through NNLO in QCD, fully differential in lepton momenta including spin-correlations, EW corrections, finite-width effects, and γ^*/Z interference. State-of-the-art codes are described in [114, 115]. Calculations to all-orders also exist, for instance the next-to-next-to-leading log-

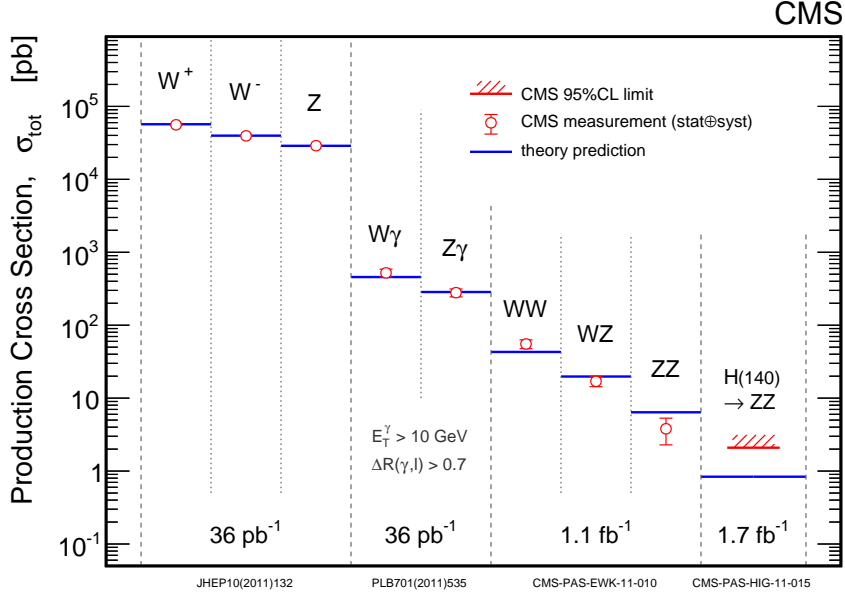


Fig. 9: Production cross-sections for processes involving gauge bosons at the LHC (at $\sqrt{s} = 7$ TeV). Figure taken from [113].

arithms (NNLL) transverse momentum resummation [116] and soft gluon resummation have been computed [117]. Threshold enhanced corrections to rapidity distributions of Z and W^\pm bosons at hadron colliders are also known at $N^3\text{LO}$ level [118]. These accurate perturbative calculations have been available for some time, and now that precise LHC data has been compared to those predictions, one can not but praise the impressive agreement between NNLO theory and experiment (see e.g. Fig. 10 and ref. [119]). One thing to note is that in these comparisons of theory with experiment, the dominant error is the theoretical one, however this is mainly dominated by the luminosity uncertainty (of the order of 4%).

At this level of precision, it is legitimate to start worrying about mixed QCD and EW corrections. QCD+EW interference is formally a higher-order effect, and exact results are not known currently. However the dominant effects come from emissions in the soft/collinear regions where an approximate factorization holds. It turns out that in general mixed corrections are small, $\mathcal{O}(0.5\%)$, but they are enhanced in the region of large transverse momenta, where they can reach up to around 5% [121].

5.2 Charge asymmetry

The natural extension of the inclusive cross-section is the $R_W = W^+/W^-$ ratio. One can then study R_W as a function of kinematical variables, e.g. one can look at the charge asymmetry as a function of lepton rapidity η

$$A(\eta) = \frac{R_W(\eta) - 1}{R_W(\eta) + 1}. \quad (3)$$

This measurement is very sensitive to PDFs since in the ratio asymmetric properties of PDFs are enhanced, while many uncertainties cancel. Fig. 11 shows the relative good agreement of theoretical predictions that use various PDFs with ATLAS data. It also illustrates how the shape of the theoretical prediction is sensitive to the PDFs chosen. Indeed, ATLAS and CMS measurements of this distribution have been already used by the Neural Network (NN) collaboration to constraint PDFs. In particular a reduction of uncertainty of the order of 10 – 30% in the range $x = [10^{-3}, 10^{-1}]$ was obtained for the valence- and sea-quark distributions. It is interesting to observe that LHCb data at larger rapidities probe

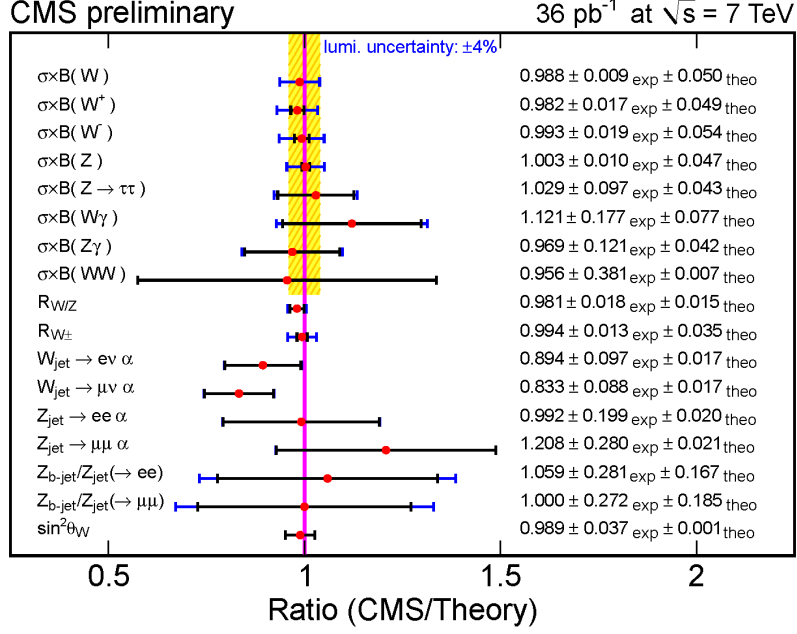


Fig. 10: Comparison of NNLO theory and CMS data for Drell-Yan observables. Figure taken from ref. [120].

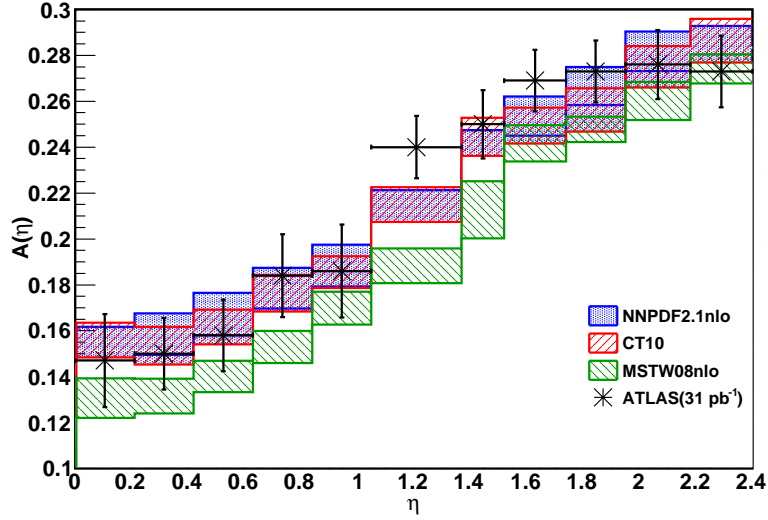


Fig. 11: Predictions for the W lepton asymmetry at NLO, obtained with DYNNLO [114] using the CT10 [122], MSTW08 [123] and NNPDF2.1 [124] parton sets, compared to measurements for the muon charge asymmetry from ATLAS [125] (7 TeV). Figure taken from ref. [126].

larger and smaller values of x that are currently less constrained. They will therefore soon have a larger impact in PDF determination than ATLAS and CMS have.

5.3 Production of W/Z boson in association with jets

At the LHC, because of the large energy, the production of W and Z bosons in association with jets is very likely. This is illustrated in Fig. 12 which shows the differential distribution for H_T , the total transverse energy of the event, for various jet multiplicities. Since the cross-sections with an additional jet is rescaled in the figure by a factor 10^{-1} compared to the cross-section with one less jet, it is evident that at

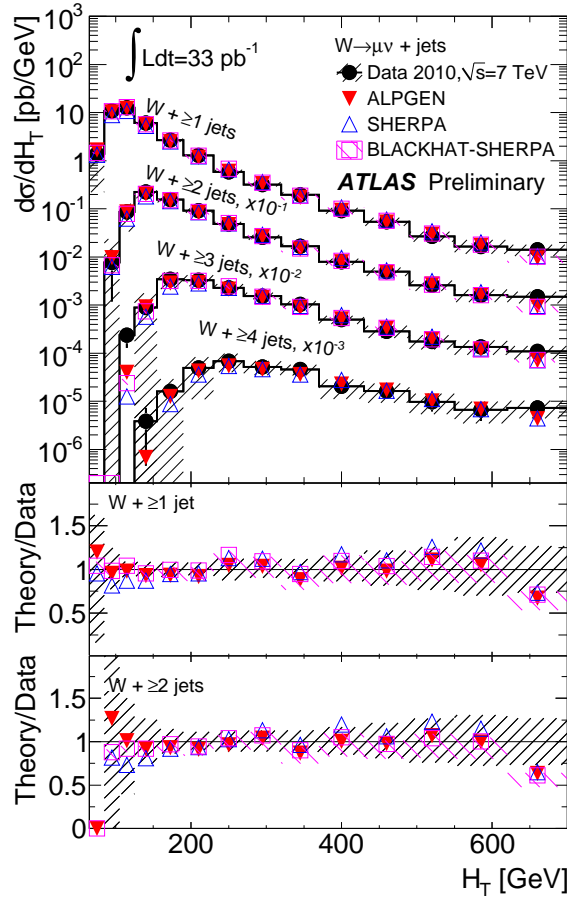


Fig. 12: Cross-section for $W \rightarrow e\nu$ and jets at the LHC (7 TeV) as a function of the total transverse momentum of the event H_T . Figure taken from [127].

high H_T (a region of particular interest for various new-physics searches), all jet-multiplicities contribute similar amounts.² Because of this, it becomes very important to have a good perturbative control of processes involving the production of W/Z bosons together with many jets. The perturbative calculation of processes involving a large number of jets is quite difficult beyond LO. However, as discussed in Sec. 2.2, recent years have seen a revolution in the techniques used for NLO calculations. These novel techniques allowed in the last five years the calculation of a large number of processes involving gauge bosons and jets. In particular, while $V + 1$ and $V + 2$ jets have been described to NLO in QCD since 1983 [128, 129] and 2002 [130–132], to quote a few examples we know now at NLO $VV + 1$ jet [133–136], $W + 3$ jets [25, 26], $Z + 3$ jets [27], W^+W^+ plus dijets [30], W^+W^- plus dijets [31], W^+W^-bb [29, 37] and $W + 4$ jets [44] and $Z + 4$ jets [45]. Furthermore, various vector boson fusion (VBF) induced gauge boson production processes have been computed and are available in the public code VBFNLO [39].

Fig. 13 shows the transverse momentum distribution for the four p_t ordered jets in $Z + 4$ jets production. The middle pane illustrates the typical reduction of the dependence of the cross-section on renormalization and factorization scale at NLO, compared to LO. It is however also evident that while for some distributions (e.g. $p_{t,j4}$) the ratio of LO/NLO is flat, in other cases the shape of the NLO distribution is different from the LO one, so that LO/NLO has a non-flat slope. Is it also interesting to look at the ratio of Z/W^+ and Z/W^- displayed in the lower pane. The agreement of LO and NLO predictions for these ratios illustrates the excellent perturbative control that one can achieve at NLO on these ratios.

²Of course, this statement depends on the precise definition of the jets, in particular on their p_t cut.

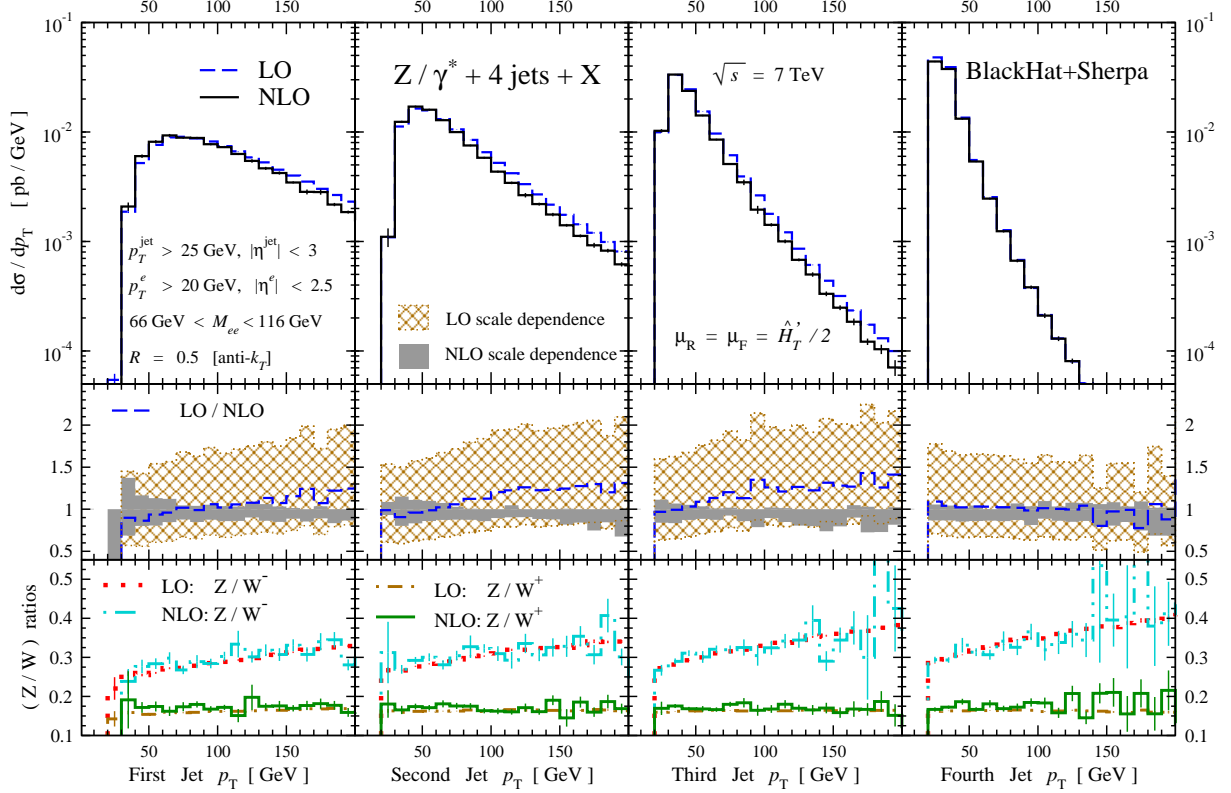


Fig. 13: Transverse momentum distributions of the leading four jets in $Z + 4\text{-jet}$ production at the LHC (7 TeV). Figure taken from [45].

Furthermore, the fact the Z/W^+ is flat, while Z/W^- rises with the p_t can be attributed to the fact that both W^+ and Z production are dominated by the u -quark distribution, while W^- is mainly produced from d quarks in the protons, therefore the Z/W^- ratio displays the slope of the u/d -quark distributions as a function of the jet transverse momenta.

5.4 Di-boson production and anomalous couplings

The ZZ , WW , WZ di-boson production of processes that have been implemented recently in the POWHEG BOX. The calculation includes γ^*/Z interference, single resonant contributions, interference effects for identical fermions and, for WW and WZ the effect of anomalous couplings. The gluon-gluon fusion contribution, that is formally NNLO, but is important when Higgs search cuts are applied, is available the gg2WW and gg2ZZ generators [137–139], and, recently, also from the program MCFM [140].

A pure NLO calculation, as implemented earlier in MCFM [141, 142], reveals that for these processes the conventional scale variation of the LO result is very modest but underestimates completely the size of the NLO corrections. E.g. for $pp \rightarrow W^+W^- \rightarrow e^+\nu_e\mu^-\nu_\mu$ production at the 7 TeV LHC without any cuts, the LO cross-section using NNPDF2.1 [124] is $375.2^{+1.6}_{-3.8}$ fb, while the NLO cross-section is 499.8^{+12}_{-10} fb [143]. Here the error denotes the scale uncertainty. Similar results (with smaller cross-sections) are obtained for the other processes. The reason for the large NLO corrections (not caught by the LO scale variation) is that new partonic channels open up at NLO. It is therefore clear that only a NLO calculation can provide a reliable estimate of the cross-section and of its error. These di-boson production processes are particularly interesting since they are important backgrounds to Higgs searches. Furthermore, they are sensitive to new physics at high scales through the measurement of anomalous trilinear couplings (ATGCs). Indeed, while the LHC does probe new physics at the TeV scale directly, ATGCs indirectly probe physics in the multi-TeV range, since they arise when high-energy degrees of

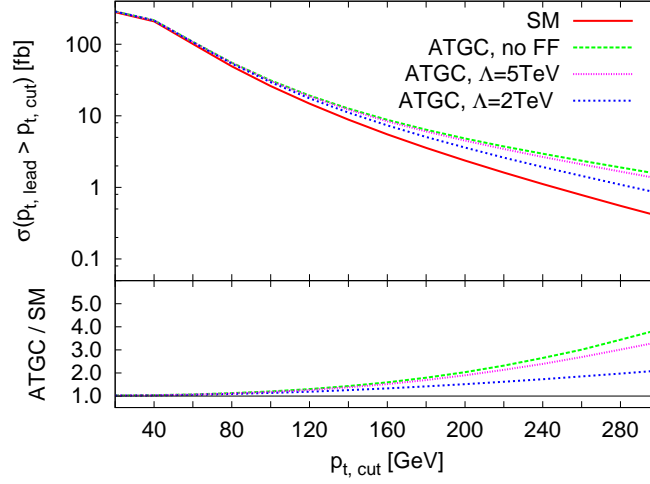


Fig. 14: The integrated cross-section for W^+W^- production at the LHC (7 TeV) as a function of the cut on the transverse momentum of the leading lepton is shown on the right. Figure taken from [143].

freedom are integrated out. Both the Tevatron [144–146] and LEP [147] were able to place quite stringent bounds on ATGCs. However, since their effects are enhanced at high energies, one expects even better bounds from the LHC. Indeed, CMS already presented bounds on the anomalous couplings appearing in an effective Lagrangian with the parametrization of ref. [148] without form factors [149].

Following refs. [148, 150, 151], one can parametrize the most general terms for the WWV vertex ($V = \gamma, Z$) in a Lagrangian that conserves C and P as

$$\mathcal{L}_{\text{eff}} = ig_{WWV} \left[g_1^V (W_{\mu\nu}^* W^\mu V^\nu - W_{\mu\nu} W^{*\mu} V^\nu) \right. \\ \left. + \kappa^V W_\mu^* W_\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W_{\mu\nu}^* W_\rho^\nu V^{\rho\mu} \right], \quad (4)$$

where $W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $g_{WWZ} = -e \cot \theta_W$ and $g_{WW\gamma} = -e$. In the SM $g_1^V = \kappa_1^V = 1$, and $\lambda^V = 0$. Any departure from these values ($\Delta g_1^V = g_1^V - 1$ etc.) would be a sign of new physics. In the POWHEG generator, all six parameters can be set independently.

In the presence of anomalous couplings, the effective Lagrangian of eq. (4) gives rise to interactions that violate unitarity at high energy. Thus, in order to achieve a more realistic parametrization, the couplings are multiplied by form factors, that embody the effects arising from integrating out the new degrees of freedom. The precise details of the form factors therefore depend on the particular model considered. Paralleling the discussion of ref. [152], in the POWHEG BOX it is assumed that all anomalous coupling Δg are modified as

$$\Delta g \rightarrow \frac{\Delta g}{(1 + M_{VV}^2/\Lambda^2)^2}, \quad (5)$$

where M_{VV} is the invariant mass of the vector boson pair and Λ is the scale of new physics.

Fig. 14 sets the anomalous coupling to the maximum deviation from the SM allowed by LEP bounds and displays the sensitivity of the transverse momentum of the leading jet in W^+W^- events to anomalous couplings, for the case of a form factor $\Lambda = 2$ TeV, $\Lambda = 5$ TeV, and no form factor ($\Lambda = \infty$). The plot illustrates the great potential of the LHC to improve on existing bounds (even more so, when the machine will run at yet higher energy).

For the production of four charged leptons, a similar NLO study (again including all off-shell, spin-correlation, virtual-photon-exchange, and interference effects) can be performed with the aMC@NLO

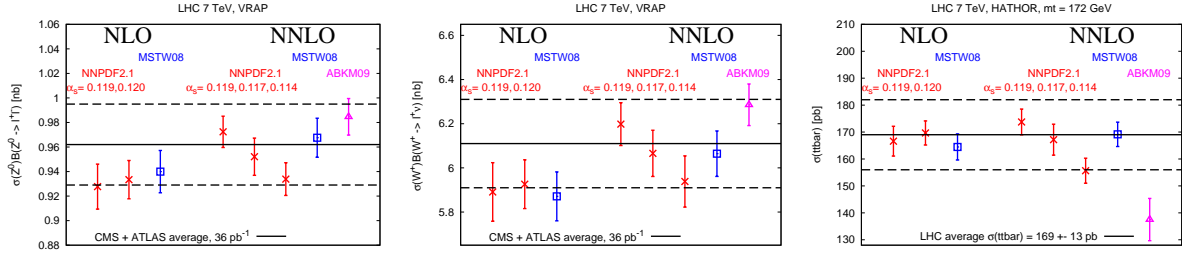


Fig. 15: The total cross-section for Z , W^+ , and $t\bar{t}$, at the LHC (7 TeV) for NNPDF2.1 with $\alpha_s(M_Z) = 0.119$ (NLO and NNLO), $\alpha_s(M_Z) = 0.120$ (NLO) and $\alpha_s(M_Z) = 0.114, 0.117$ (NNLO), MSTW08 with $\alpha_s(M_Z) = 0.1202$ (NLO) and $\alpha_s(M_Z) = 0.1171$ (NNLO), and ABKM09 with $\alpha_s(M_Z) = 0.1135 \pm 0.0014$ (NNLO). Uncertainties shown correspond to 1σ . The band corresponds to the combination of CMS and ATLAS measurements. Figure taken from ref. [124].

generator [153]. The parton showering can be done either with HERWIG and (for the first time in this context) with Pythia 6. The $O(\alpha_s^2)$ contribution of the gg channel is also included directly here, as obtained from MadLoop [46]. In the study of ref. [153] several key distributions together with the corresponding theoretical uncertainties are presented. A further theoretical improvement is that scale and PDF uncertainties are computed at essentially no extra CPU-time using re-weighting techniques.

6 Parton distribution functions and α_s

PDFs are the second thing one can not live without, if one works on LHC physics. Huge effort is devoted today in understanding differences and improving the theoretical and statistical treatment of PDFs. This activity is reflected in new PDFs sets being released by various groups [154]. The main focus of all groups is now directed towards NNLO PDFs sets, an improvement in the treatment of heavy quarks, an introduction of flexible parametrization, a more dynamic tolerance, and, of course, towards the inclusion of more data in the fits. Discussions are ongoing that try to clarify whether discrepancies between different PDFs are due to the inclusion of different data sets. For instance, there is no full consensus on what impact of the Tevatron jet data has on gluon distributions at the LHC.

Fig. 15 shows the uncertainty on three LHC benchmark processes (Z , W^+ , and $t\bar{t}$ from the left to the right) coming from using different PDFs or a different value of α_s , at NLO and at NNLO. Differences are due to the inclusion of different data in the fits, due to a different methodology (e.g. the parametrization), due to a different treatment of heavy quarks, and due to a different default value of the coupling constant. In particular, it is remarkable how much benchmark processes depend on the value of α_s . The preliminary 2011 average value of α_s is $\alpha_s = 0.1183 \pm 0.0010$ [155]. It is interesting to note that the value barely changed compared to the 2009 number ($\alpha_s = 0.1184 \pm 0.0007$) [156], but that the uncertainty on it increased. This is due to the inclusion of new data in the fits which tend to move the average value in opposite directions. An open issue today, in the combination of the various measurements to produce a world average for α_s , is the treatment of outliers that have very small errors. This is the case for the extraction of α_s from thrust computed at N³LL including power corrections using SCET [157], for the number obtained from τ -decays in [158], and for the hadronic event shapes in e^+e^- collisions at OPAL using NNLO+NLLA theoretical predictions [159], just to quote the most important cases.

New processes added to the world average since 2009 include inclusive jets at the Tevatron [160], the e^+e^- 3-jet rate which is known to NNLO [161], and $e^+e^- \rightarrow 5$ jets, which is now known at NLO [162]. The use of the Tevatron jet data in this context is particularly interesting: while the error on α_s from this extraction is not particularly small, this measurement and the sensitivity of benchmark processes on the value of α_s shown in Fig. 15 raises the question of whether it is possible to make com-

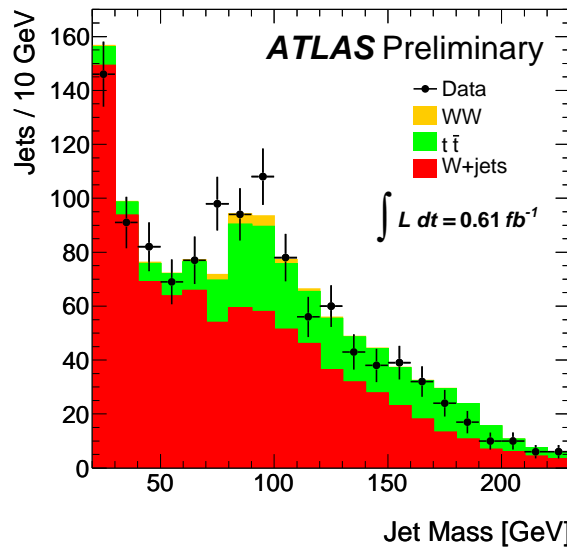


Fig. 16: Jet mass in W + jets for a jet with substructure compatible with $WZ(\rightarrow bb)$ or $WH(\rightarrow bb)$ events. Figure taken from ref. [166].

petitive measurements of α_s at the LHC. The extraction of the value of the coupling constant at hadron colliders must take into account that PDFs themselves do depend on α_s . A viable possibility then is to consider appropriate ratios (e.g. $W/(Z + (n + 1)\text{jets})/(Z/(W + n\text{jets}))$).

7 Jet algorithms

Jet algorithms are the third thing you can not live without, if you work on LHC physics. For a long time, infrared (IR) unsafe algorithms were used at the Tevatron, with several “patches” introduced to minimize the effect of the IR-unsafety. At the LHC, both ATLAS and CMS have adopted as default the anti- k_t algorithm [163]. Given that this algorithm was proposed only three years ago, it shows how flexible experimentalists are today in adopting new, successful ideas.³ Using this algorithm both collaborations have already explored scales up to 4 TeV and could place constraints on various BSM models, in particular those models that would give rise to a resonance in the M_{jj} distribution (such as massive coloured bosons, black-holes, ...).

Other IR-safe algorithms like the Cambridge-Aachen or SIScone are in use as well. These are particularly useful for studies which exploit the fact that when a massive boosted object decays, it gives rise to a “fat jet” with a non-trivial jet-substructure. Looking at the internal structure of these jets using jet-grooming techniques like filtering, pruning or trimming has a huge potential for making discoveries “easier” [164, 165]. These techniques have a big gain in sensitivity over traditional methods, but one might lose many events when imposing strict kinematical cuts and requiring a boosted regime. The potential of these studies has been demonstrated in several examples [164, 165]. However sophisticated jet studies are still a young field, and as of now there are no precise rules on how to make discoveries easier. What is impressive, is that even these very new techniques are already being used at the LHC. Fig. 16 shows for instance the single hadronic jet mass in W + jet events in a boosted regime, an observable relevant for $WH(\rightarrow bb)$. In Fig. 16 the Z peak coming from $WZ(\rightarrow bb)$ is evident, these very first results seem therefore very promising in finding a possible peak to due Higgs production.

³A minor downside to this is that ATLAS and CMS use a different radius – the choices for ATLAS are 0.4 and 0.6, while for CMS they are 0.5 and 0.7.

8 Conclusions

The physics programme at the LHC is very rich: it spans from most precise measurements, e.g. in the case of Drell-Yan, to searches with highest reach for new physics either direct searches, or indirect ones (e.g. through the potential presence of anomalous couplings). This experimental programme at the LHC is supplemented by robust theoretical predictions that include NLO QCD corrections, mixed NLO-QCD+EW corrections, NNLO, and resummation of logarithmically enhanced contributions. Furthermore, different calculations are merged using clever matching procedures that catch the best features of different calculations. From the theoretical community, there is a clear and successful effort to produce predictions and public codes that have the flexibility required for today's sophisticated experimental analysis (e.g. including parton shower, decays with spin correlations, massive quark effects, etc.).

Impressive results have already come out of the LHC, but this is certainly only the tip of the iceberg. After just one year of running at the LHC some measurements, e.g. in processes involving W/Z production, start being dominated by theoretical and parton density errors. It will therefore be a real challenge for theorists to keep up with the high experimental precision.

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